Understanding Microgravity

MICROGRAVITY RESEARCH DIVISION

Artwork by John Frassanito and Associates

What Is Microgravity?

Gravity is such an accepted part of our lives that we rarely think about it, even though it affects everything we do. Any time we drop or throw something and watch it fall to the ground, we see gravity in action. Although gravity is a universal force, there are times when it is not desirable to conduct scientific research under its full influence. In these cases, scientists perform their experiments in microgravity — a condition in which the effects of gravity are greatly reduced, sometimes described as "weightlessness." This description brings to mind images of astronauts and objects floating around inside an orbiting spacecraft, seemingly free of Earth's gravitational field, but these images are misleading. The pull of Earth's gravity actually extends far into space. To reach a point where Earth's gravity is reduced to one-millionth of that on Earth's surface, one would have to be 6.37 million kilometers away from Earth (almost 17 times farther away than the Moon). Since spacecraft usually orbit only 200–450 kilometers above Earth's surface, there must be another explanation for the microgravity environment found aboard these vehicles.

Any object in freefall experiences microgravity conditions, which occur when the object falls toward the Earth with an acceleration equal to that due to gravity alone (approximately 9.8 meters per second squared [m/s^2], or 1 g at Earth's surface). Brief periods of microgravity, or µg, can be achieved on Earth by dropping objects from tall structures. Longer periods are created through the use of airplanes, rockets, and spacecraft. The microgravity environment associated with the space shuttle is a result of being in orbit, which is a state of continuous freefall around the Earth. A circular orbit results when the centripetal acceleration of uniform circular motion ($\mathbf{v}^2/\mathbf{r}$; $\mathbf{v}$ = velocity of the object, $\mathbf{r}$ = distance from the center of the object to the center of the Earth) is the same as that due to gravity alone.

On the cover: Illustration of a U.S. space shuttle docked with the future International Space Station, including components to be provided by the space agencies of Canada, Europe, Japan, Russia, and the United States

Why Conduct Research in Microgravity?

A microgravity environment provides the basis for a unique laboratory in which scientists can investigate the three fundamental states of matter: solid, liquid, and gas. Microgravity conditions allow scientists to observe and explore phenomena and processes that are normally masked by the effects of Earth's gravity.

The Microgravity Research Program

NASA's Office of Life and Microgravity Sciences and Applications (OLMSA) is responsible for planning and executing scientific research that benefits from access to microgravity. Within OLMSA, the Microgravity Research Division (MRD) oversees the study of important physical, chemical, and biological processes in a microgravity environment.

Initial research into the effects of microgravity began in the early years of the space program and included space experiments conducted during the Apollo, Skylab, and Apollo-Soyuz programs during the 1960s and 1970s. With the milestone of its first launch in 1981, the space shuttle program stimulated the development of microgravity research instruments that could be flown, modified, and flown again, enabling scientists to design experiments based on the results of previous investigations.

The challenges facing NASA's microgravity research program are to use spaceflight opportunities wisely and to conduct the most scientifically promising research possible. The MRD is responsible for guiding a comprehensive research program, which is currently made up of five major areas: biotechnology, combustion science, fluid physics, fundamental physics, and materials science. The MRD seeks out and coordinates researchers with a wide range of backgrounds, forming an interdisciplinary microgravity science community that conducts research for and disseminates the results of the science program. The MRD also supports the science community's research through the development of suitable experiment instruments for selected projects and the selection of the most suitable vehicle for each experiment.

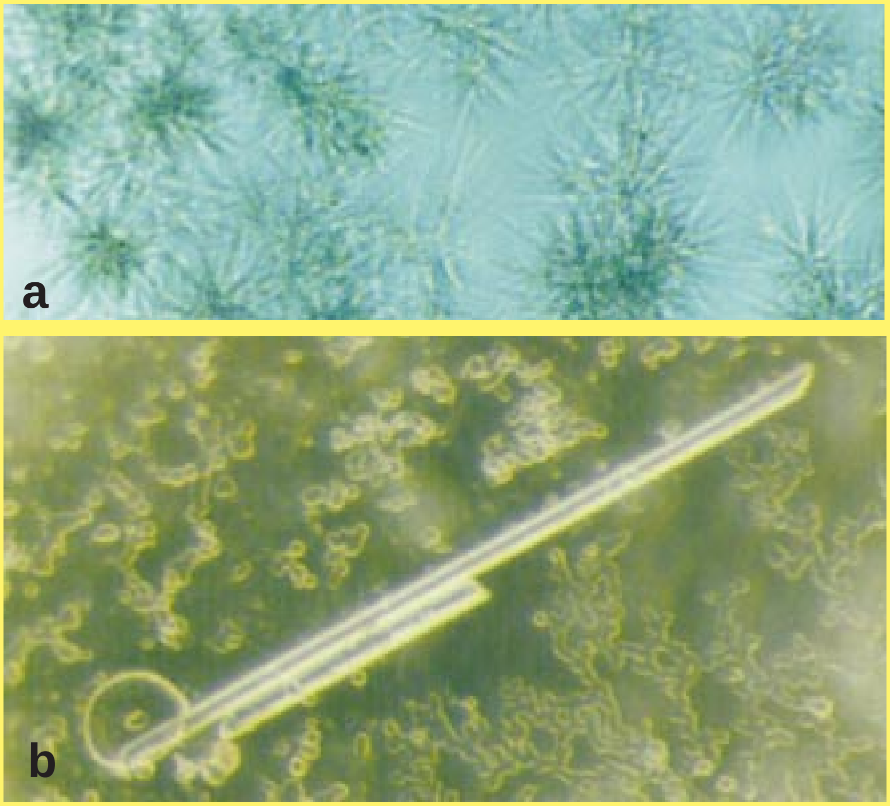
The results of MRD-sponsored experimental investigations are used to challenge and validate contemporary scientific theories, to identify and describe new physical phenomena that can be only explored in a microgravity environment, and to engender the development of new theories as a result of unexpected or unexplained discoveries — often the most exciting part of research. Experiment results are made available to the wider scientific community through published work and participation in conferences and workshops. The MRD also coordinates educational outreach programs to bring information to educators, students, and the general public. Because the sharing of information is a major objective of the microgravity research program, the MRD strives to disseminate experiment results as quickly as possible and to assist industry in understanding potential technological applications of those results.

Microgravity Research Disciplines

Biotechnology

Biotechnology is an applied biological science that involves the research, manipulation, and manufacturing of biological molecules, tissues, and living organisms. With a critical and expanding role in health, agriculture, and environmental protection, biotechnology is likely to play an important role in our lives and our economy in the next century. NASA's microgravity biotechnology program focuses on three principal areas of research: protein crystal growth, mammalian cell and tissue culture, and fundamental biotechnology.

Scientists are studying proteins because they perform many functions in the human body. These functions include transporting oxygen and chemicals in the blood, forming major components of muscle and skin, and fighting disease. Viruses, which are also protein structures, are of interest to researchers as well. They seek to understand the structure of proteins and viruses by growing protein and virus crystals suitable for structural analysis by X-ray diffraction. Research indicates that many



Photos courtesy of Dr. Jean-Pierre Wery and Eli Lilly and Co.

*These images of crystals of the protein raf kinase, which is important to cancer research, compare results of ground-based crystal growth (**a**) to crystal growth in microgravity (**b**). The long, thin crystals in photo **b** are approximately an order of magnitude larger than the small, needle-like crystals in photo **a**. The space-grown crystals, which were grown during the second United States Microgravity Laboratory (USML–2) mission in November 1995, were the largest crystals of raf kinase ever produced. Large, uniform crystals like these generally yield better structural information when analyzed through X-ray diffraction, which in turn can lead to a better understanding of how the structure of a protein is related to its function in the human body.*

crystals of these materials grown in low gravity yield substantially better structural information than crystals grown on Earth, since the effects of gravity adversely influence the crystals' development.

The microgravity biotechnology program has also shown the benefits of using a low-gravity environment for growing organic cells and tissues. On Earth, most tissue cultures grow in flat trays, but growing such tissues in reduced-gravity facilities has produced three-dimensional structures that are larger and more representative of tissues found in the human body. This has been accomplished by using bioreactors, which are horizontal cylinders that rotate to inhibit the full effects of gravity, both on Earth and aboard the space shuttle. Using these methods of study, scientists have been able to cultivate and study both cancerous and healthy cells and tissue. As scientists become more successful in cell and tissue culturing, they will have to rely less often on human subjects for their studies.

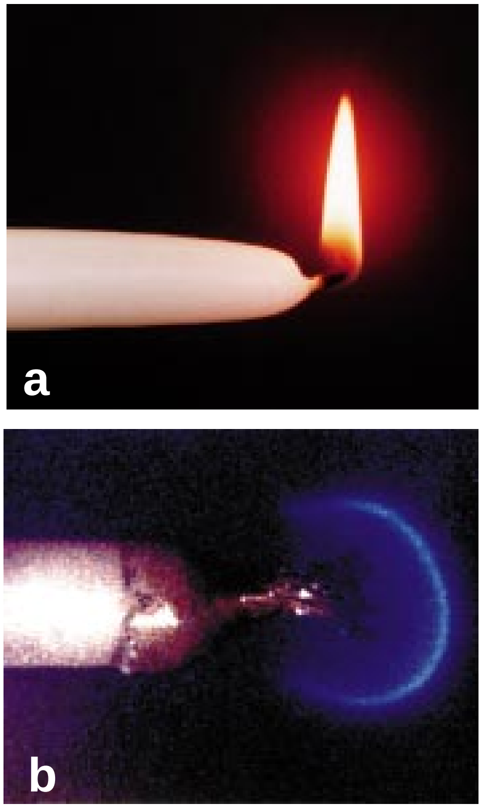
Fundamental biotechnology opens the door to the exploration of biotechnological processes and biophysical phenomena that might be studied in the space environment. Fundamental research areas in biotechnology that can be applied to biological systems include separation science and technology, molecular and cellular aggregation, the behavior of electrically driven flows, and capillary and surface phenomena.

Marshall Space Flight Center in Huntsville, Alabama, is NASA's Microgravity Center of Excellence for biotechnology and is supported by the biotechnology program office at Johnson Space Center in Houston, Texas.

Combustion Science

The microgravity combustion science program supports research in how flames ignite, spread, and extinguish under microgravity conditions. Combustion, or burning, is a rapid, self-sustaining chemical reaction that releases a significant amount of heat. Examples of common combustion processes are burning candles, forest fires, log fires, the burning of natural gas in home furnaces, and the burning of gasoline in internal combustion engines.

Combustion is a key element of many of modern society's critical technologies.



*On Earth, gravity-driven buoyant convection causes a candle flame to be teardrop-shaped (**a**) and carries soot to the flame's tip, making it yellow. In microgravity, where convective flows are absent, the flame is spherical, soot-free, and blue (**b**).*

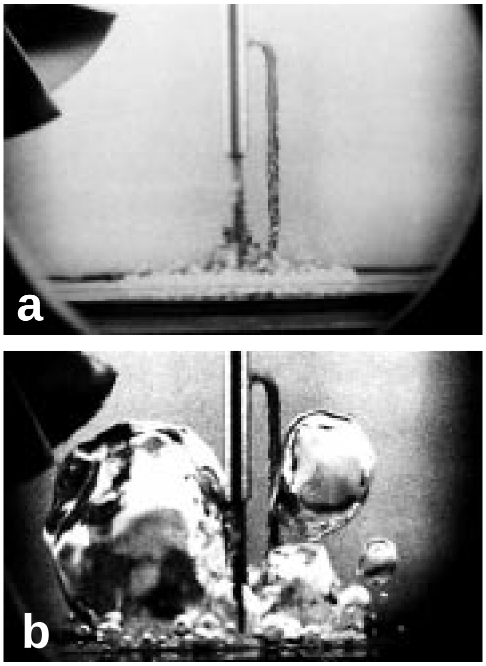
Electric power production, home heating, ground transportation, spacecraft and aircraft propulsion, and materials processing can use combustion to convert chemical energy to thermal energy or propulsive force. Although combustion, which accounts for approximately 85 percent of the world's energy usage, is vital to our current way of life, it poses great challenges to maintaining a healthy environment. Improved understanding of combustion will help us deal better with the problems of pollutants, atmospheric change and global warming, unwanted fires and explosions, and the incineration of hazardous wastes.

Despite vigorous scientific examination for over a century, researchers still lack a full understanding of many fundamental combustion processes. The ability to conduct more controlled experiments in space, without the complication of gravity, provides scientists with an opportunity to examine these complicated processes closely. The objectives of NASA's microgravity combustion science program are to improve understanding of fundamental combustion phenomena affected by gravity, to use research results to advance combustion science and technology on Earth, and to address issues of fire safety in space.

Lewis Research Center in Cleveland, Ohio, is NASA's Microgravity Center of Excellence for combustion science.

Fluid Physics

A fluid is any material that flows in response to an applied force; thus, both liquids and gases are fluids. Some arrangements of solids can also exhibit fluid-like behaviors; granular systems (such as soil) can respond to extraordinary forces, like those induced by earthquakes or floods, with a flow-like shift in the arrangement of solid particles and the air pockets or liquids that fill the spaces between them. Fluid physicists seek to better understand the physical principles governing fluids, including how fluids interact with solid boundaries; how fluids flow under the influence of energy, such as heat or electricity; how particles and gas bubbles suspended in a fluid interact with and change the properties of the fluid; and how fluids change phase,



*When a liquid is heated from the bottom to the boiling point in Earth's gravity (**a**), small bubbles of heated gas form near the bottom of the container and are carried to the top of the liquid by gravity-driven convective flows. In the same setup in microgravity (**b**), the lack of convection and buoyancy allows the heated gas bubbles to grow larger and remain attached to the container's bottom for a significantly longer period.*

either from fluid to solid or from one fluid phase to another. Fluid phenomena studied range in scale from microscopic to the size of the atmosphere and include everything from the transport of cells in the human body to changes in the composition of the atmosphere. The universal nature of these phenomena makes their study fundamental to science and engineering.

Microgravity fluid physicists use microgravity environments to increase our knowledge of fluid behavior in order to advance science and technology. Understanding the fluid-like behavior of soils under stress will help civil engineers design safe buildings in earthquake-prone areas. Materials engineers can benefit from a better grasp of how the structure and properties of a solid metal are determined by fluid behavior during its formation. And knowledge of the flow characteristics of vapor-liquid mixtures is useful in designing power plants to ensure maximum stability and performance.

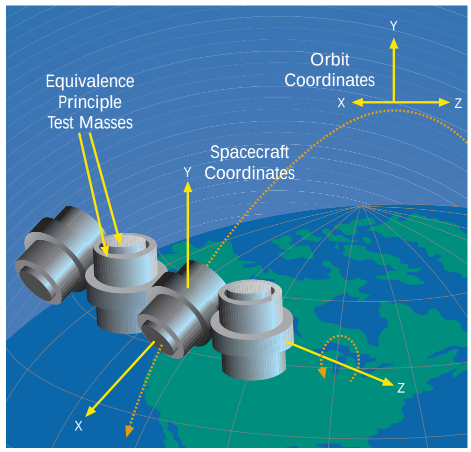
The work of fluid physics researchers often applies to the work of other microgravity scientists. Materials science researchers rely on the knowledge of principles of fluid physics for materials processing. For example, impurities in materials such as glasses and alloys can be reduced by managing fluid behavior while the material is in a molten state. This is desirable because impurities may degrade sought-after properties of materials, such as corrosion resistance, mechanical toughness, and optical transmissivity. In addition, knowledge of fluid flow in microgravity can help combustion scientists improve fire safety and fuel efficiency.

Lewis Research Center in Cleveland, Ohio, is NASA's Microgravity Center of Excellence for fluid physics.

Fundamental Physics

Fundamental physics is the study of the basic laws that govern the properties of the physical world on all scales, from microscopic to cosmic. The discipline of fundamental physics continues to evolve as new technology and techniques improve and broaden the scope of scientific principles that can be experimentally investigated. The study of fundamental physics in the microgravity environment can yield entirely new or substantially improved results when the obscuring effects of Earth's gravity are not present. Researchers will use the microgravity environment to test some of the most fundamental theories of physics, such as Einstein's theory of general relativity and Newton's laws concerning gravitation.

Until recently, the work of microgravity fundamental physics focused primarily on condensed matter physics at extremely low temperatures, with a particular emphasis on investigations of liquid helium. Scientists have observed that at these extremely low temperatures, sometimes close to absolute zero (-273° C), some materials, like helium, will experience unusual phase transitions to states of matter that cannot be simply classified as gas, liquid, or solid. These states include superfluidity, in which a fluid flows without friction and has a very high thermal conductivity, and superconductivity, in which a material conducts electricity or heat with no resistance or loss of energy. Superconductors are used to make high-strength, lower-power magnets for medical applications (such as magnetic resonance imaging, or MRI) as well as high-precision thermometers. Superconductors can also be used for magnetic shielding and may soon be applied in the power and transportation industries.



The Satellite Test of the Equivalence Principle (STEP), pictured at top, will carry concentric test masses to Earth orbit to test a fundamental assumption underlying Einstein's Theory of General Relativity: that gravitational mass is equivalent to inertial mass. STEP is a 21st-century version of the test that Galileo is said to have performed by dropping a cannonball and a musket ball simultaneously from the top of the Leaning Tower of Pisa to compare their accelerations. During the STEP experiment, four pairs of test masses will be falling around the Earth, and their accelerations will be measured by superconducting quantum interference devices (SQUIDs). The extended time in microgravity, or freefall, and the extreme sensitivity of the instruments will allow the measurements to be a million times more accurate than those made in modern ground-based tests.

Another area of research in microgravity fundamental physics, and one which is relatively new, is laser cooling and atomic physics. Researchers working in this area are interested in the study of the structure of isolated atoms and their interactions with external stimuli, such as other atoms, surfaces, electromagnetic fields, temperature, pressure, and light. Laser cooling technology provides a new method of investigation in which atoms are bombarded with light to slow their movement, allowing scientists a longer time to observe them. Microgravity will improve this technology by eliminating the external stimulus of gravity, which affects the motions of atoms.

Fundamental physics research will also play a significant role in the human exploration and development of space. Engineers have already designed atomic clocks, which use laser-cooled atoms to maintain high-precision time standards. These clocks can be used to help spacecraft maintain accurate courses over vast distances and to help aircraft make more precise landings in situations that require automatic landing systems, such as in inclement weather or when visibility is limited.

The Jet Propulsion Laboratory in Pasadena, California, is NASA's Microgravity Center of Excellence for fundamental physics.

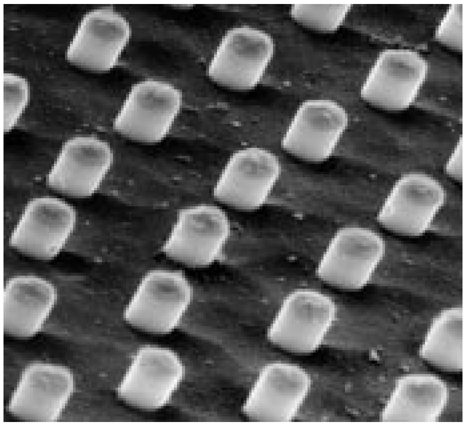
Materials Science

Materials science is an extremely broad field that encompasses the study of all materials. Materials scientists seek to understand the formation, structure, and properties of materials on various scales, ranging from atomic to microscopic to macroscopic (large enough to be visible) levels. Establishing relationships between the structures of materials, their properties, and the way they are produced is fundamental to the study of materials.

Longitudinal section of a gallium-doped germanium crystal grown in a sounding rocket experiment. In the bottom portion of the crystal, which solidified under gravity conditions, the gallium concentration of the solid varies, as evidenced by the random striations. The top portion grew under microgravity conditions, where the lack of buoyancy-induced convection allowed for a uniform mixture as the melt solidified.

The microgravity materials science program uses the unique characteristics of the microgravity environment to study fundamental issues in materials solidification and crystal growth. Of particular interest is the study of the roles of buoyancy-driven convection, sedimentation, and hydrostatic pressure in the formation of electronic and photonic materials, metals, alloys, composites, glasses, ceramics, and polymers.

Materials science research in microgravity may lead to better understanding of the processes used to produce these materials on Earth. Such knowledge can be used to design better process control strategies on Earth. Microgravity experimentation may eventually allow the production of limited sample quantities of high-quality materials or of samples exhibiting unique properties for use as theoretical “benchmarks.” In addition, researchers may also find ways to combine materials in order to obtain unique structures in microgravity that ordinarily would not form under the effects of Earth’s gravity. This may lead to the creation of new types of materials that perform better than current materials or that have properties unlike any available today.



An etched sample of a monotectic alloy processed in microgravity. Monotectics solidify from a liquid of uniform composition to form a solid and a liquid of different compositions than the original liquid. Solidifying these materials in microgravity is the only way to form a solid alloy with an evenly distributed microstructure.

Marshall Space Flight Center in Huntsville, Alabama, is NASA’s Microgravity Center of Excellence for materials science.

Microgravity Research Missions

NASA has allocated significant resources aboard the space shuttle for microgravity research. The Microgravity Science Laboratory (MSL) series, the United States Microgravity Laboratory (USML) series, and the United States Microgravity Payload (USMP) series were and are crucial to the success of NASA’s Microgravity Research Division. Many of the missions included in these series took advantage of a specially designed microgravity laboratory facility called Spacelab.

The product of an extremely successful international partnership between NASA and the European Space Agency (ESA), Spacelab is a series of modular components that can be assembled into unique mission configurations. The components, which fit into the cargo bay of the space shuttle, consist of pressurized laboratory sections, pallets, and associated hardware. Spacelab has proven invaluable to microgravity scientists, since it provides them with a shirt-sleeve laboratory environment with the resources (power, cooling, data communication, etc.) necessary to conduct state-of-the-art experiments.

The International Microgravity Laboratory (IML) series and the Life and Microgravity Spacelab (LMS) mission are examples of missions that successfully combined life science research and microgravity research. Life science experiments require a great deal of crew time but little power or room for equipment, while microgravity experiments require more power and cargo space but less crew time; therefore, they fit together nicely. The IML and LMS missions have also proven to be valuable testing grounds for international collaboration.

International Cooperation

International cooperation has played a large part in NASA-sponsored missions, providing a strong foundation for efforts to create more permanent laboratory facilities in space. The planned International Space Station will include participation from Belgium, Canada, Denmark, France, Germany, Italy, Japan, the Netherlands, Northern Ireland, Norway, Russia, Spain, the United Kingdom, and the United States. As part of the groundwork for this project, space shuttle crews have successfully completed docking missions with *Mir*, the Russian space station, and have exchanged experiments, facilities, and astronauts and cosmonauts several times. The NASA/*Mir* program has provided the opportunity to conduct experiments that require more extended periods of microgravity than the shuttle can provide and has furnished a model of international collaboration.

Microgravity Research Facilities

NASA's Microgravity Research Division supports both ground-based and flight experiments requiring microgravity conditions of varying duration and quality. These experiments are conducted in the following facilities:

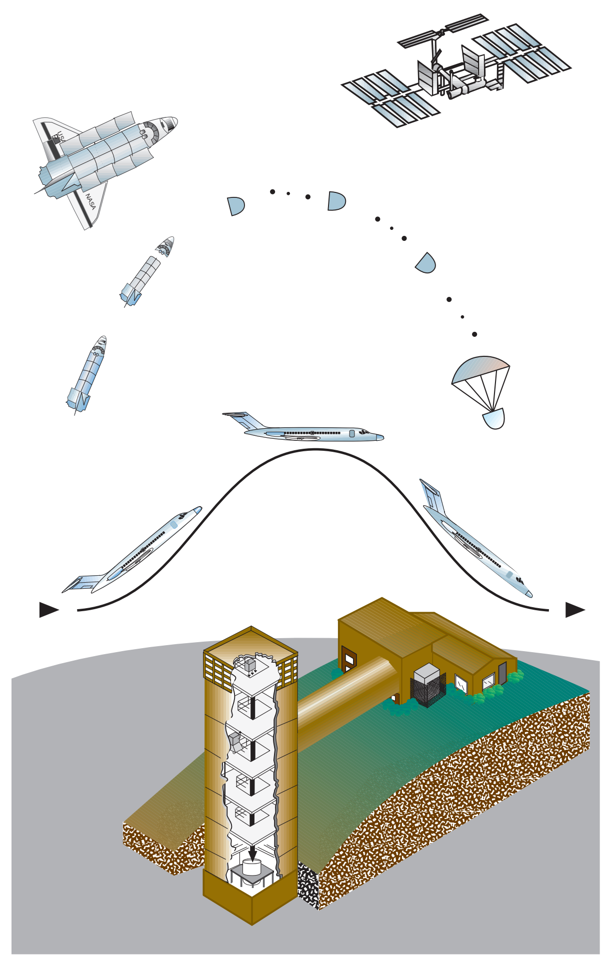
A **drop tower** is a long vertical shaft used for dropping experiment packages, enabling them to achieve microgravity through freefall. Various methods are used to minimize or compensate for air drag on the experiment packages as they fall. Lewis Research Center in Cleveland, Ohio, has two drop facilities (one 24 meters tall and one 132 meters deep) that can accommodate experiments which need only a limited amount of time (2.2 or 5.2 seconds) in microgravity or which are test runs of experiments that will later be performed for longer periods in an aircraft, rocket, or spacecraft.

Reduced-gravity aircraft are flown in parabolic arcs to achieve longer periods of microgravity. The airplane climbs rapidly until its nose is at an approximate 45-degree angle to the horizon. Then the engines are briefly cut back, the airplane slows, and the nose is pitched down to complete the parabola. As the plane traces the parabola, microgravity conditions are created for 20–25 seconds. As many as 40 parabolic trajectories may be performed on a typical flight.

Sounding rockets produce higher-quality microgravity conditions for longer periods of time than airplanes. An experiment is placed in a rocket and launched along a parabolic trajectory. Microgravity conditions are achieved during the several minutes when the experiment is in freefall prior to re-entering Earth's atmosphere.

A **space shuttle** is a reusable launch vehicle that can maintain a consistent orbit and provide up to 17 days of high-quality microgravity conditions. The shuttle, which can accommodate a wide range of experiment apparatus, provides a laboratory environment in which scientists can conduct long-term investigations.

A **space station** is a semipermanent facility that maintains a low Earth orbit for up to several decades. The facility enables scientists to conduct their research in microgravity over a period of several months without having to return the entire laboratory to Earth each time an experiment is completed.



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